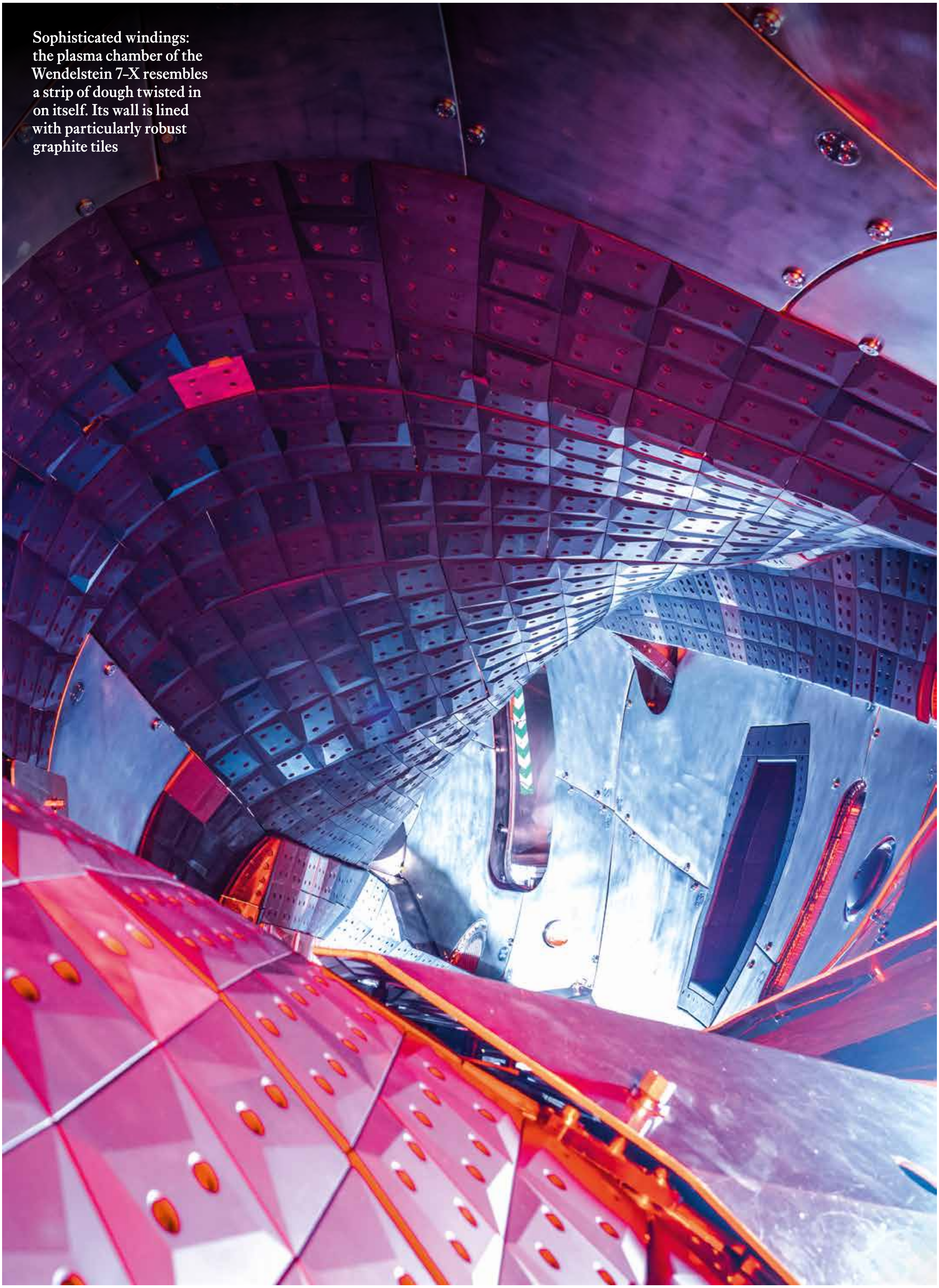

Sophisticated windings: the plasma chamber of the Wendelstein 7-X resembles a strip of dough twisted in on itself. Its wall is lined with particularly robust graphite tiles

PHOTO: JAN HOSAN / MPI FOR PLASMA PHYSICS

FOCAL POINTS IN NUCLEAR FUSION

TEXT: ANDREAS MERIAN

The National Ignition Facility in the USA announced a breakthrough in fusion research in December 2022. Nuclear fusion offers the promise of a clean and practically inexhaustible source of energy. The Max Planck Institute for Plasma Physics is also working on ways to harness this. The institute's scientific director, Sibylle Günter, and director emeritus, Karl Lackner, share insights into where some of the public and private fusion projects stand – and how they compare to the concepts their institute is researching.

A glass of seawater contains as much energy as a barrel of oil. But unlike the more than 300 kilograms of CO_2 released when 159 lIters of oil are burned, no greenhouse gases are produced when energy is extracted from water. However, in order to be able to access this energy at all, we must first master nuclear fusion. It offers the enormous promise of practically unlimited energy, and clean energy at that – which is to say: it also wouldn't produce long-lived radioactive waste. Nuclear fusion would be an ideal addition to renewable energy sources in seasons and areas with little wind and sun.

Fusion energy is produced when light nuclei fuse together. This, however, only occurs naturally under conditions such as those found in the sun. Scientists and engineers alike have been trying to achieve the technical prerequisites for decades. But because fusion research is still a long way off from being used in an energy-producing power plant, some people sarcastically refer to it as the "fusion constant": generating electricity from a fusion reactor is always thirty or even fifty years in the future.

Iter is currently the largest and most expensive fusion project in the world, with a current estimated cost of 18 to 22 billion euros. The name stands for International Thermonuclear Experimental Reactor and is a research project undertaken by the EU, USA, China, India, South Korea, Japan, and Russia. The Max Planck Institute for Plasma Physics is also involved. Iter is expected to release about ten times as much fusion energy as goes into starting the fusion reaction. But Iter will not generate electricity. This will first happen in a demonstration power plant, which is being planned under the simple name of Demo and is intended to test the interactions between all of the power plant's components. It will be built as soon as the Iter experiments are complete. That, however, may be a while yet.

Iter was originally scheduled to begin operations back in 2016. It was then said that the reactor would be up and running in 2025 and able to produce fusion power in 2035. But it was recently announced that even this timeline would not be met. "Iter is not a purely scientific project; it also has a political component," says Sibylle Günter, Director at the Max Planck Institute for Plasma Physics in Garching. Political constraints also create technical difficulties. This is because the partner countries not only share the financing, but also the development and production. "This means

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that the individual components of the reactor are manufactured in the different countries, which results in some things not fitting together as planned," says Sibylle Günter. Iter's press release also mentioned "extensive repairs".

Meanwhile, many private enterprises have also started working on nuclear fusion despite, or perhaps because of, the painstaking progress of this large-scale, government-funded project. After all, the prospect of unlimited clean energy is incredibly exciting. According to the Fusion Industry Association, 33 companies around the world are trying to achieve just that. Some of them are pursuing fundamentally different technical approaches to nuclear fusion and are promising both their investors and the general public that fusion energy will soon be commercially viable. The companies have raised more than $4.7 billion in investments to date to achieve this goal. Although start-ups are certainly more agile than government projects such as Iter, they are often on much shakier ground in terms of scientific and technical feasibility. "The current mainstream research approaches are compromises," says Karl Lackner. The director emeritus at the Max Planck Institute for Plasma Physics in Garching spent decades researching nuclear fusion and experienced both progress and unexpected obstacles in the process – the same process on which Iter is based. "A reactor like Iter presents a solution to all the problems we've identified so far – it's not the optimal solution for any of them, but it's at least a sufficient solution for all of them. A few of the alternative approaches do an excellent job of solving one problem and are, therefore, exciting. But the other problems are proving more difficult or may even be impossible to solve."

All of the approaches have one thing in common: they are modeled after the process by which the sun generates energy. In it, the nuclei of hydrogen atoms fuse to form helium at a pressure of around 200 billion bar and a sweltering 15 million degrees Celsius. Under these conditions, matter exists as plasma, meaning that electrons and positively charged atomic nuclei are no longer bound to each other. The high temperature provides the positively charged nuclei with the necessary speed to overcome the electrostatic repulsive force between them. The pressure inside the sun also compresses matter to the point that it becomes more likely that two nuclei will collide. It is not technically feasible to achieve this pressure on Earth, which is why much higher temperatures are required in fusion reactors to trigger the fusion of nuclei. Ordinary hydrogen atoms also fuse much too slowly for technical use. However, a technically feasible solution was found in physics more than seventy years ago: the fusion of heavy and superheavy hydrogen – also known as deuterium and tritium. The Max Planck Institute for Plasma Physics is investigating two of the oldest concepts for a fusion reactor. Researchers at the Garching site are experimenting with the Asdex Upgrade, which, like Iter, is a tokamak. A tokamak is a donut-shaped vessel within which a strong plasma current is used to confine the electrically charged plasma particles. By contrast, the Greifswald site is working on the Wendelstein 7-X reactor, a stellarator. The stellarator also constrains the plasma in a ring-shaped vessel using a magnetic field, which is, however, produced purely by currents in external conductors. In this case, however, his plasma vessel and magnetic field resemble a strip of dough twisted in on itself several times rather than a smooth doughnut.

The first task for both types of reactors is to trap the hydrogen plasma with the magnetic field in such a way that the charged particles do not touch the wall if possible. If the plasma makes too much contact with the vessel, it will cool down too much and make a self-sustaining fusion reaction impossible. Although the geometry of the magnetic field in the tokamak is simpler than in the stellarator, a current must flow through the plasma ring in the tokamak, which introduces some practical problems for efficient power plant operation. These problems do not appear in a stellarator. "Conceptually, the stellarator is better suited for a fusion power plant," Günter explains. "However, a stellarator's magnetic field has to be optimized, which is only possible with sufficient knowledge of physics and computing power. This is why fusion research initially took the simpler approach of the tokamak." Demo is currently also planned as a tokamak. If, however, the stellarator concept proves to be superior by the time construction begins, these plans could still be overturned. The fact that both the stellarator and the tokamak are being researched at the Max Planck Institute for Plasma Physics is unique for any research facility worldwide. This enables a level of objectivity that is important in ba-

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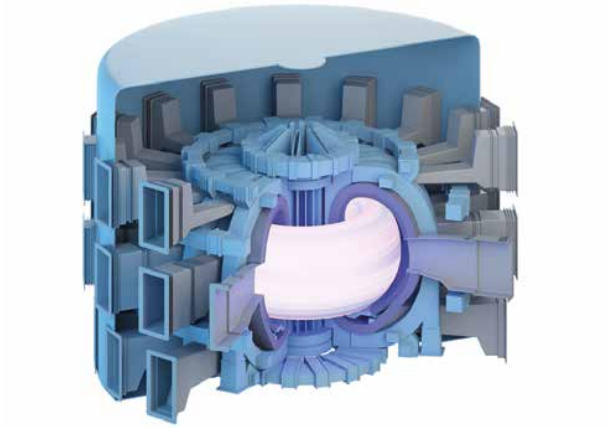
SUMMARY

Nuclear fusion has the potential to provide practically unlimited clean energy and is, therefore, being researched in some large-scale government research projects such as Iter, Asdex Upgrade, and Wendelstein 7-X, as well as many start-up companies.

The intention is for Iter to deliver more energy than goes directly into triggering nuclear fusion, but it keeps getting delayed. To operate, however, Iter also requires more energy than nuclear fusion generates and it does not produce electricity. The Demo power plant is intended to do just that.

Some of the private initiatives have announced very ambitious timelines, which should be viewed skeptically. These often provide a very good solution for one problem posed by nuclear fusion, but do not adequately address others.

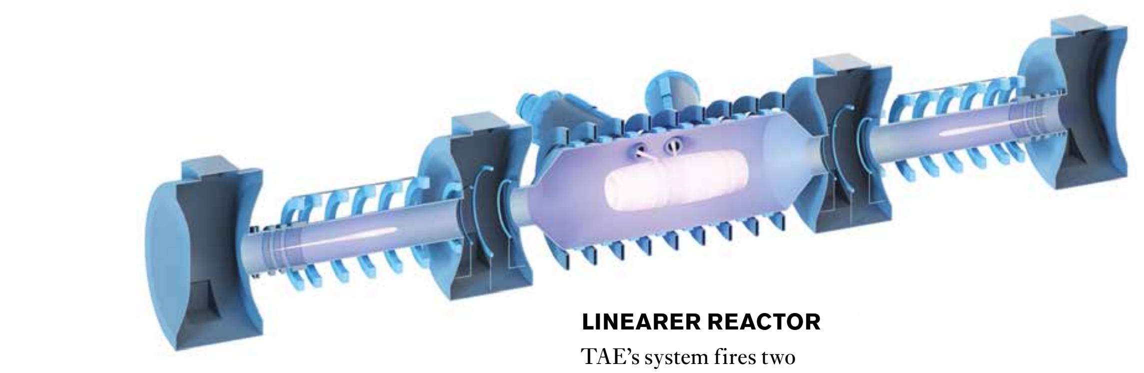


TOKAMAK

The Asdex Upgrade, Iter, and potentially Demo have plasma chambers that are shaped like a doughnut.

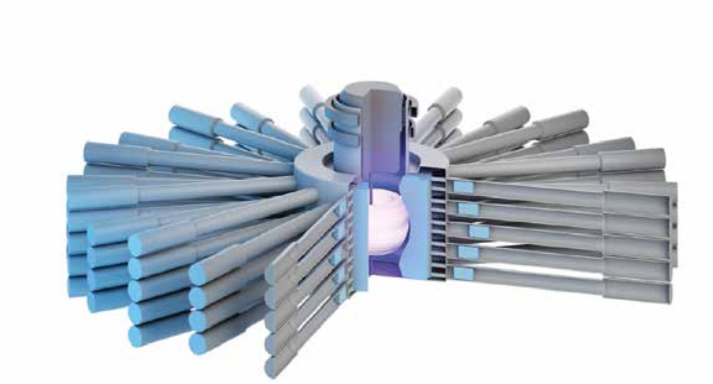
STELLARATOR

A winding magnetic field encloses the plasma in the plasma chamber, which is shaped in the same way, for instance in the Wendelstein 7-X.



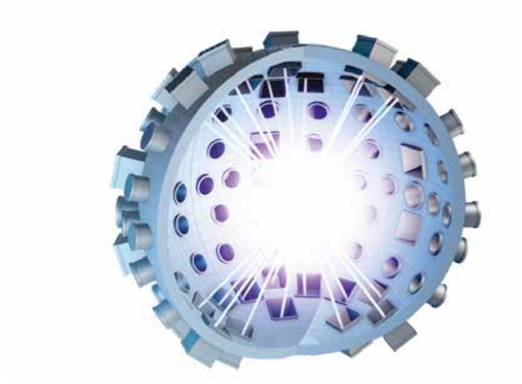
LINEARER REACTOR

TAE's system fires two plasma packages at each other, producing rotating cylindrical plasma.



MODIFIED TOKAMAK

General Fusion generates plasma in a container of rotating liquid metal that is compressed with pistons to ignite it.



INERTIAL CONFINEMENT FUSION

The NIF and some start-up companies are exploiting the inertia of mass that holds the plasma together after it has been compressed and heated with powerful lasers.

ILLUSTRATION: P. BALL, THE RACE TO FUSION ENERGY, NATURE, VOLUME 599 ISSUE 7886, 25 NOVEMBER 2021; TRÄGEHEITSFUSON: GCO

sic research, says Sibylle Günter: “We are not locked in and can compare and openly discuss the pros and cons. In addition, the research conducted on both types of facilities benefits the other.”

Small tokamak with powerful magnets

In order to reach the necessary temperature for fusion in both types of reactors, the hydrogen plasma is heated by firing in fast hydrogen atoms, using electromagnetic radiation, and, in the case of the tokamak, also by the resistance of the plasma current. Once the conditions are finally right, the nuclei of deuterium and tritium fuse, and a helium nucleus and a neutron are created, both with considerable kinetic energy. The magnetic cage is permeable to uncharged neutrons, allowing the particle to penetrate the vessel wall with full energy. The resulting heat is to be used to generate electricity in the same way as in a conventional power plant. The material in the wall, however, remains as slightly radioactive waste.

Commonwealth Fusion Systems is also among the startups focusing on the tokamak design. The company even announced that its prototype Sparc should be operational in as little as five years. They are aiming to achieve this with a tokamak that is much smaller than Iter and which can be modified more quickly and cost-effectively to produce a reactor that is ready for the market. In order to confine the plasma in it, much stronger magnetic fields are required. Consequently, at the core of Sparc are novel magnetic coils made of high-temperature superconductors that are more powerful than Iter’s superconducting coils and require less cooling. Research into this technology was conducted for a long time at MIT in Cambridge, Massachusetts, giving rise to the start-up. “I’m happy that Commonwealth Fusion Systems is continuing to explore the high-field approach,” says Karl Lackner. “There is a good chance of success, since the basic principle has been tried and tested for a long time. Having said that, experience has taught us to be skeptical when it comes to announced timelines.” Nevertheless, Commonwealth Fusion Systems was able to convince private investors of its idea: the startup raised more than $1.8 billion last year.

The merger start-up TAE Technologies also has strong support from Google, and not just financially. Google is also helping by providing computing power and expertise in the field of artificial intelligence. “TAE is taking an old approach that has only regained traction with the use of advanced feedback techniques,” explains Karl Lackner. TAE combines particle accelerators and magnetic coils to create a plasma cylinder that is roughly the shape of a tin can without a lid or bottom. The cylinder rotates like a roller, which stabilizes it – but only temporarily. Without additional measures, its rotation would gradually slow down and the plasma cylinder would eventually collapse. It was only through extensive calculations with the support of Google that TAE was able to get an understanding of the instabilities and control them through feedback loops. Karl Lackner is impressed by this progress, but he is also critical: “TAE is currently at the same stage as research on tokamaks in the 1970s and 1980s in terms of the triple product, i.e., the combination of temperature, particle density, and confinement time, but most importantly, it still has a particle density that is far too low.” The triple product is a measure of how close the plasma comes to the conditions for self-sustaining nuclear fusion. In 2019, TAE had not yet reached the value achieved by the predecessor of Asdex Upgrade at the Max Planck Institute for Plasma Physics in 1989. Moreover, like a few other companies, TAE is not pursuing the fusion of tritium and deuterium, but of boron and protons. This would eliminate the need for tritium, which is radioactive and difficult to obtain, and would not result in a radioactive reactor wall. “It is, however, much more difficult to fuse boron and proton, and the yield is also lower,” says Karl Lackner.

While TAE’s progress was based on theoretical calculations, General Fusion’s breakthrough is expected to come from innovative engineering. In both the conventional tokamak and the stellarator, the interaction between the reactor wall and the plasma presents a problem. Consequently, fusion research has been searching intensively for years for the right materials for the reactor wall. General Fusion is taking a different approach

Typical large construction site: the Iter fusion reactor is being built at the Cadarache research center in France – but there have been repeated delays. The plasma chamber will run through the loop-shaped elements when it is finished.

from mainstream research here: they are attempting to enclose the plasma with liquid metal. The metal will not be destroyed by the interaction with the plasma and therefore, does not need to be repeatedly replaced. Moreover, the wall of liquid metal facilitates the dissipation of fusion energy in the form of heat. General Fusion is employing a modified tokamak design for the reactor. To do this, the liquid metal is made to rotate in the reactor. It is pressed against the wall of the vessel in the same way as laundry during a spin cycle, creating a cavity in the center. The deuterium and tritium plasma will be introduced into this cavity. However, in order to ignite the plasma, i.e., to start nuclear fusion, it needs to be further compressed. In order to accomplish this, General Fusion plans to use precisely controlled pistons mounted all around the reactor wall to compress the liquid metal and its plasma core. But Lackner also believes that this is one of its biggest challenges: “The compressed plasma is likely to be unstable.” Despite this, General Fusion announced that it will be building a demonstration power plant in Culham, England, in partnership with the United Kingdom Atomic Energy Authority. This is expected to be completed in 2025, paving the way for the first commercial fusion power plants in the late 2020s or early 2030s.

What all the projects mentioned so far have in common is that they use a magnetic field to enclose the plasma. The National Ignition Facility (NIF) in the USA and the German start-ups Marvel Fusion and Focused Energy are pursuing a completely different path. They are focusing on laser-based inertial confinement fusion. In this process, the conditions required for nuclear fusion can only be achieved for a very short time, usually for a few nanoseconds. The plasma is

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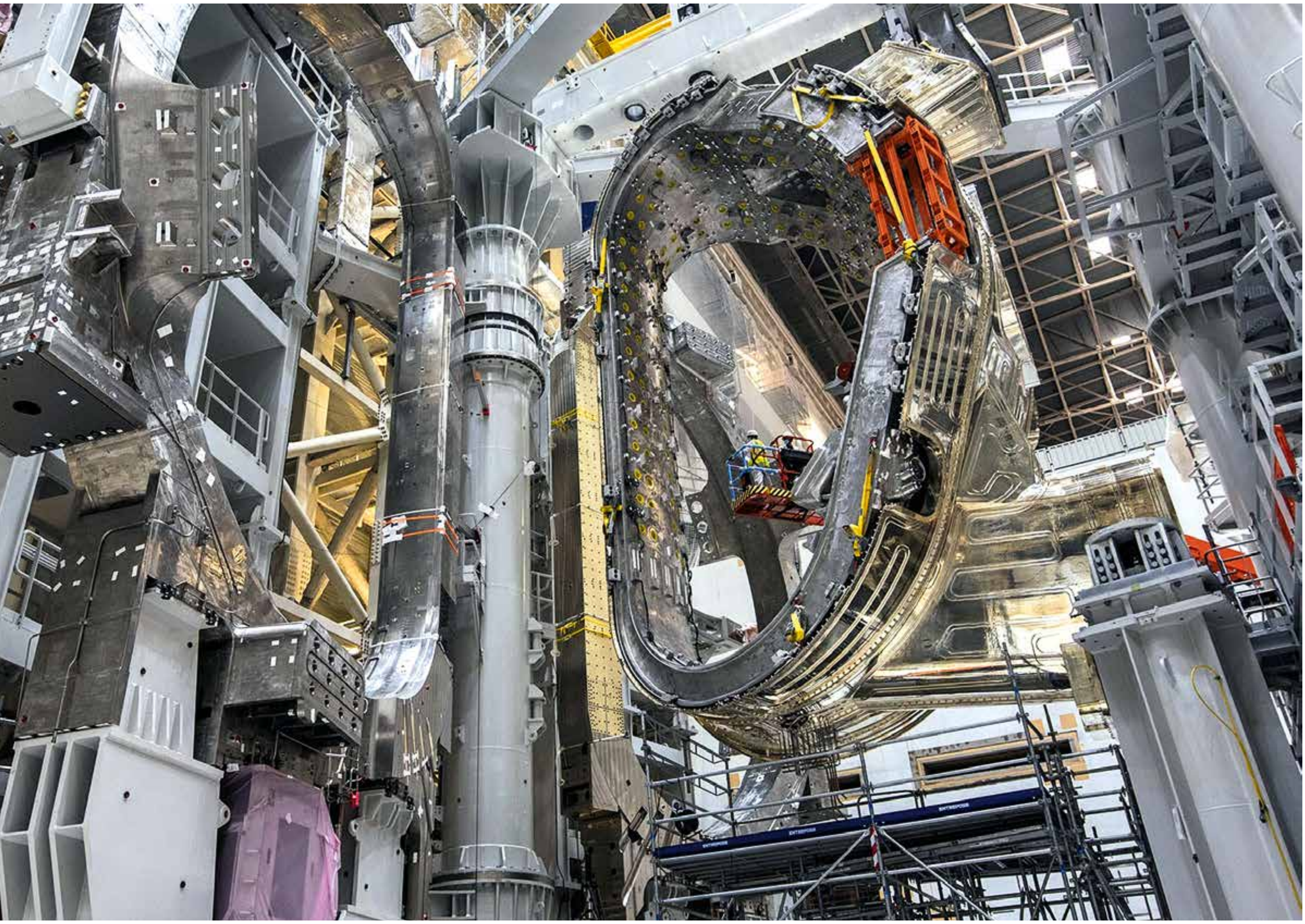

PHOTO: ITER ORGANIZATION, HTTP://WWW.ITER.ORG/

Using light power for inertial confinement fusion: the National Ignition Facility in the U.S. splits what is currently the world’s most powerful laser into multiple beams that generate X-rays in the reactor chamber. This detonates a capsule containing deuterium and tritium, creating plasma and resulting in nuclear fusion.

held together for this short time purely due to its inertia and does not have to be elaborately confined in a magnetic cage. High-powered lasers are used by the researchers to achieve the high temperature and density required for nuclear fusion within a very short time. The NIF at Lawrence Livermore National Laboratory is primarily a military research facility, since laser-based inertial confinement fusion can be used to study what happens when a hydrogen bomb is detonated. Despite this – or perhaps because of it – this facility is the most advanced system around for inertial confinement fusion. NIF uses what is currently the most powerful laser in the world. It produces the temperature and density required for fusion indirectly via multiple intermediate steps, with the laser heating the inner wall of a cavity to a temperature making it an effective radiator of X-rays. In December 2022, NIF researchers made a record-breaking shot: the nuclear fusion process released about 50 percent more energy than was input by the laser to create and ignite the plasma. The team has, however, only been able to reproduce similar successes with difficulty, since even the smallest deviations in the geometry of the experiment, among other things, can lead to large differences in the results. In any case, this approach is far from being implemented in a power plant: at present, the NIF facility can only fire four to six shots per day; a power plant would need to fire several per second.

Unlike NIF, the two German startups are aiming ultra-short laser pulses directly at a capsule containing the fuel. Focused Energy, a spin-off of the Technical University of Darmstadt, wants to first generate and compress

PHOTO: LAWRENCE LIVERMORE NATIONAL LABORATORY

the plasma by bombarding a pellet filled with deuterium and tritium with a laser beam. A second, more powerful, but shorter pulse laser should then produce fast ions heating the plasma to ignition. This two-stage approach reduces the total laser energy required, thereby saving costs. “It’s an exciting approach – if it works,” says Sibylle Günter. “And I’m skeptical of the timeline.” After all, the first power plants are expected to produce electricity in the mid-2030s – a plan that even the company itself calls challenging. Marvel Fusion’s laser-assisted inertial confinement fusion technology has a trick to it: the capsules containing the fuel have a special nanostructure. Only a few scientific details of the approach are public, however, and Günter and Lackner are accordingly skeptical. “Based on the publicly available information, it is not clear how Marvel Fusion’s approach is supposed to work,” Lackner states.

The overall energy balance causes problems

One problem is thwarting all of the approaches currently being pursued: so far, fusion reactors are nowhere near being able to produce more energy than is needed for their entire operation. When it comes to the use of nuclear fusion in power plants, it is ultimately not the energy balance of the fusion reaction that is decisive, but the net energy yield of the entire power plant. Even Iter will not be in the black. Although, it should generate more energy than flows directly into the plasma, Iter, as a power plant, would still consume more energy in total than it generates. This is because an enormous amount of energy is required to cool the large magnetic coils and to heat the plasma. Moreover, the heat generated by nuclear fusion cannot be converted into electricity without efficiency losses. In theory, Iter could cover about half of its own energy needs. With inertial confinement fusion, the difference is even greater: in the most recent and best-performing experiment to date on laser-based inertial confinement fusion at NIF, 150 percent of the energy from the laser was recovered through nuclear fusion. But generating the laser energy required about 150 times more energy than arrived in the reactor chamber. As such, the fusion reaction released only about one percent of the energy used as heat. At best, about 50 percent of this could be converted into electricity. However, the demonstration pilot power plant Demo aims to prove that nuclear fusion by magnetic confinement, at least, is capable of producing true excess energy, as long as the plant is large enough. But even if research groups someday manage to produce a self-sustaining fusion reaction with a positive energy balance, it remains to be seen whether this type of power generation will be economical.

Despite all the difficulties, fusion power remains a worthy goal. After all, the problems associated with fossil fuels are well known, and whether renewable sources such as wind and solar power will actually be able to meet humanity’s growing energy needs is still uncertain. Which of the many approaches to nuclear fusion will ultimately be successful is difficult to predict. What is clear, however, is that competition should not stifle scientific exchange: “Whether it is government-funded research or a private-sector initiative, it is important that the results are openly communicated,” says Karl Lackner. ”This way, we will definitely be able to achieve our goal more quickly.”

GLOSSARY

NUCLEAR FUSION
is the fusion of atomic nuclei. When these are light nuclei such as protons, energy is released in the process; this is how stars generate energy.

MAGNETIC CONFINEMENT
is the name of an approach to nuclear fusion in which plasma is confined in a magnetic field. This is mainly carried out in tokamak and stellarator systems, which differ in terms of how the magnetic field is generated.

INERTIAL CONFINEMENT FUSION
takes its name from the way the fusion plasma retains the necessary density for a short time due to the inertia of mass. Lasers can generate, compress, and heat the plasma.